

Higgs and Supersymmetry

at Collider Experiments



Lepton-Photon 2003

Fermilab

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Higgs:

- concentrate on MSSM scenarios
- usually expect a light SM-like Higgs
- non-standard scenarios
 - invisible Higgs $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$
 - bosophilic Higgs
 - peculiar BR scenarios
 - CP-violations
- LEP is done with the SM-like Higgs, presently investigating non-standard scenarios with rigor
- TEVATRON is getting started on SM-like signals

for a recent review, see:
Carena & Haber, [hep-ph/0208209](#)

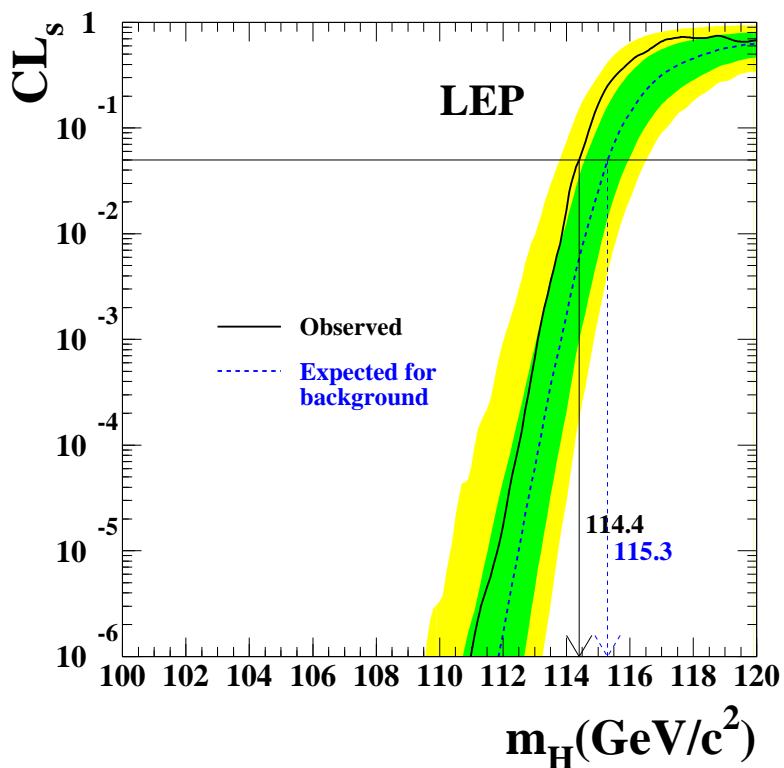
Supersymmetry:

- generic MSSM
- vs.
- the multitude of special cases: SUGRA/cMSSM (standard for comparisons), R-parity violation (RPV), gauge-mediated SUSY (GMSB), anomaly-mediated SUSY (AMSB)
- There are no absolute exclusions in Supersymmetry. . .
- emphasize the experimental signatures
 - not the models

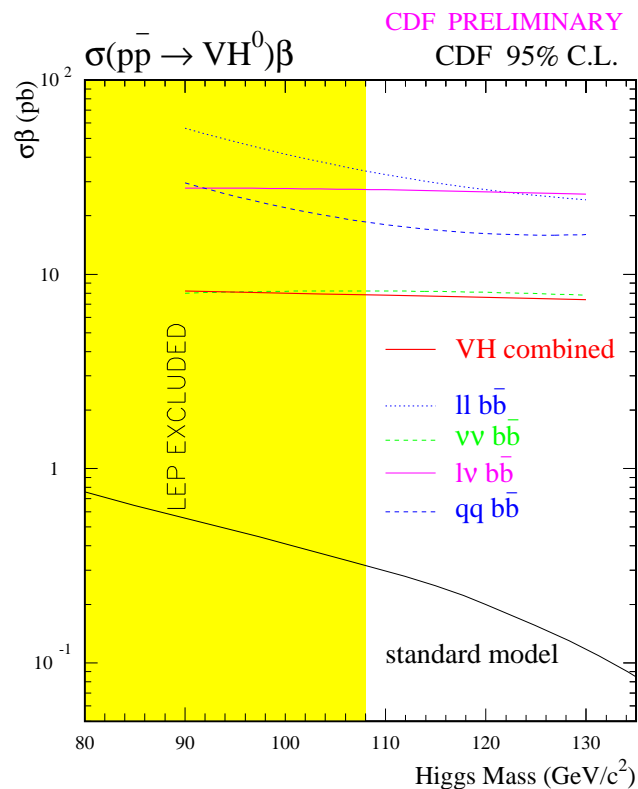
After all, the hope is to find something in real data, and theory is only a guide!

for a recent review, see:
Steve Martin, [hep-ph/9709356](#)

Standard Model Higgs Searches



Basic SM Higgs, $m_h > 114 \text{ GeV}$
no more discussion of 'hints'



No real sensitivity –
yet we hope to observe the Higgs in RUN II...

As we will see, the baton is passing from LEP to the TEVATRON...

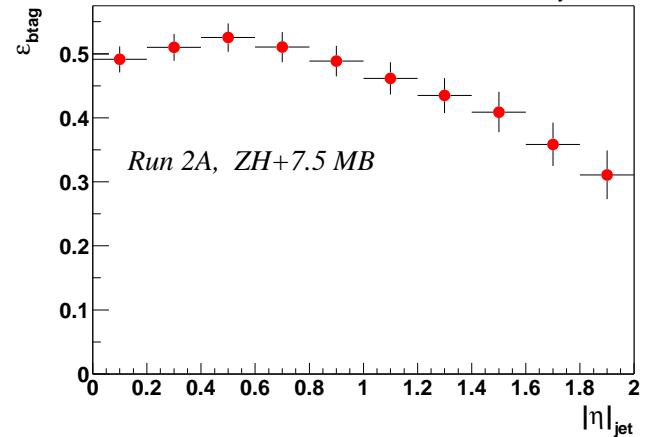
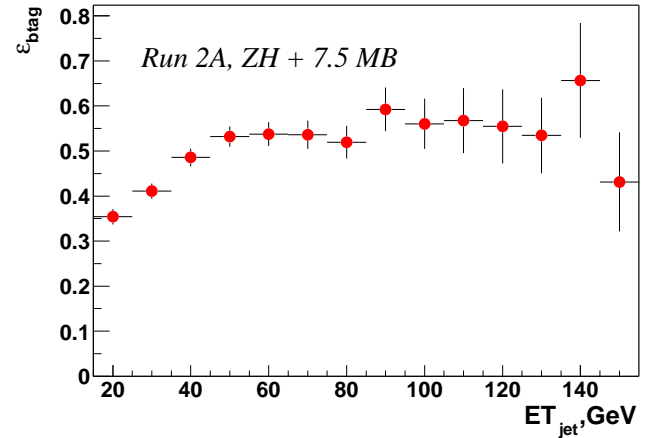
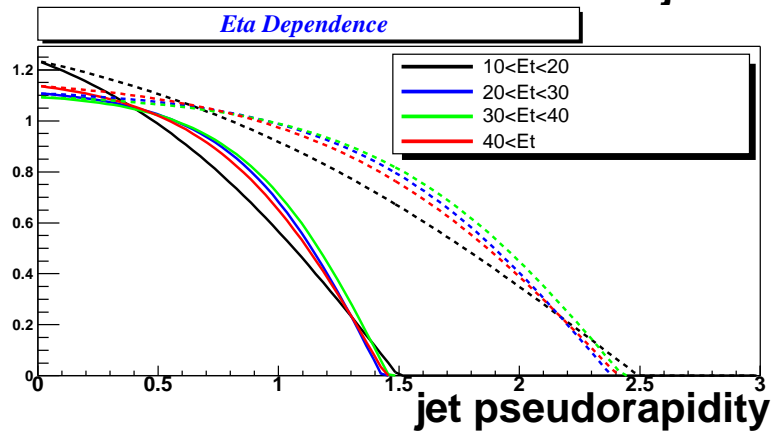
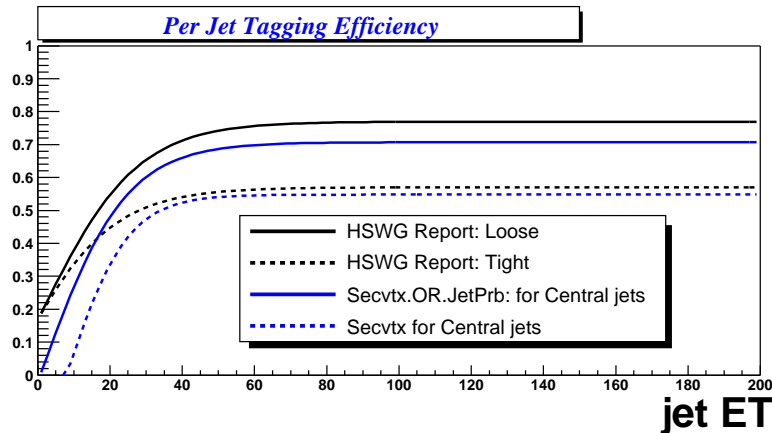
A New Study of Higgs Sensitivity

- *Goal:* update the results of the 1998-99 FNAL WS study
“Were the central assumptions on detector performance too optimistic?”
- *Scientific Justification:*
 - CDF & DØ now have tuned, hit-level simulations.
 - event selections can now be based on actual top & electroweak analyses
 - current analysis techniques (e.g., for key background estimates) can be employed
 - can – must – examine impact of multiple interactions
 - some background processes known to be higher ($\sim 20\%$)
 - what can one achieve if integrated luminosity is low?
- *Practical Approach:*
 - concentrate on $115 < m_h < 140$ GeV
 - concentrate on the two main channels:
 - CDF studied $p\bar{p} \rightarrow Wh$ with $W \rightarrow \ell\nu$ and $h \rightarrow b\bar{b}$
 - DØ studied $p\bar{p} \rightarrow Zh$ with $Z \rightarrow \nu\bar{\nu}$ and $h \rightarrow b\bar{b}$
 - results combined for both channels and experiments

Findings:

- Despite some optimistic assumptions in the old study, the conclusions are supported by this new study.
- Central b -tagging is almost as good as assumed. -see *plot*-
Some improvements should still be possible.
Hope to be able to extend to large $|\eta|$ as indicated. . .
- Optimistically, di-jet mass resolution will have a 11% core.
Perhaps it will be possible to achieve 10% with advanced techniques.
($Z \rightarrow b\bar{b}$ calibration signal will require $\sim 400 \text{ pb}^{-1}$)
- *Fitting* the mass distribution amounts to a gain of $\sim 20\%$ in luminosity, compared to counting in a mass window.
- In the CDF Wh analysis, study di-jet mass resolution and understand in detail differences w.r.t. the old baseline study.
—→ hope for some improvement from cut optimization, *etc.*
- In the $D\emptyset Zh$ analysis, employ dedicated artificial neural networks for certain backgrounds, and cut optimization of discriminating kinematic quantities. -see *plot*-
—→ rely on CDF study for di-jet mass resolution.

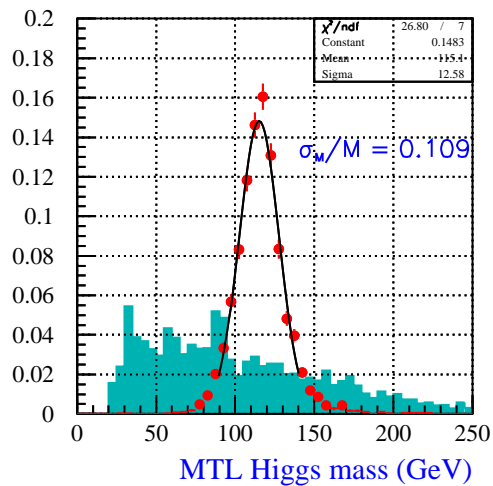
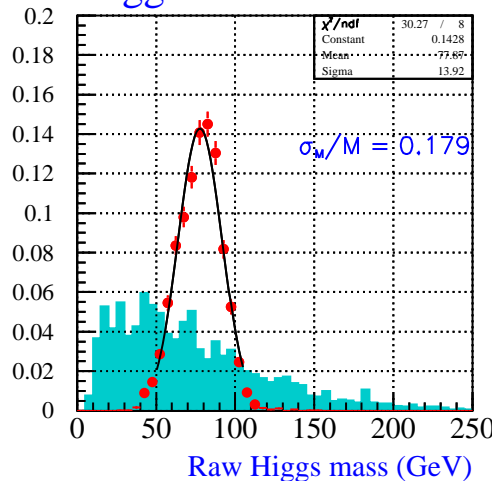
b-jet tagging



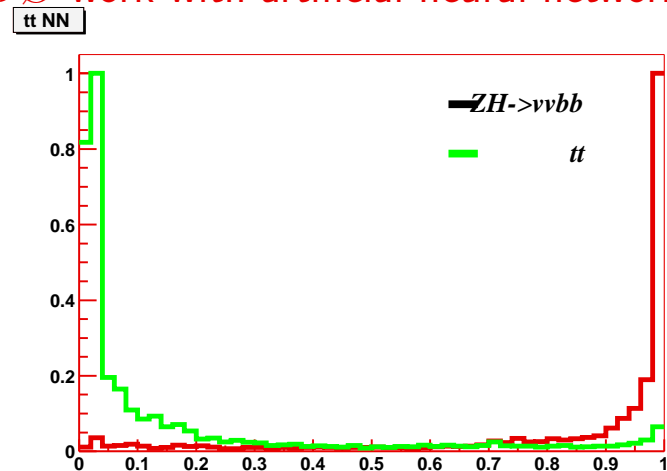
CDF study shows central jets well-tagged
& considers extensions to higher η

$D\bar{D}$ study shows some degradation for
many multiple interactions

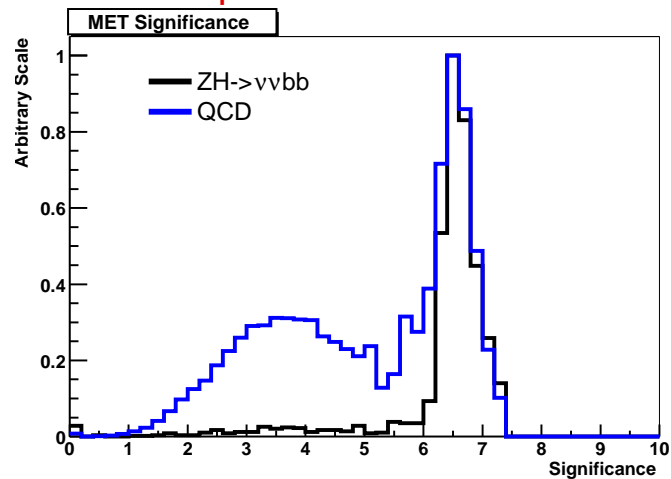
CDF work on mass resolution: Higgs mass corrections



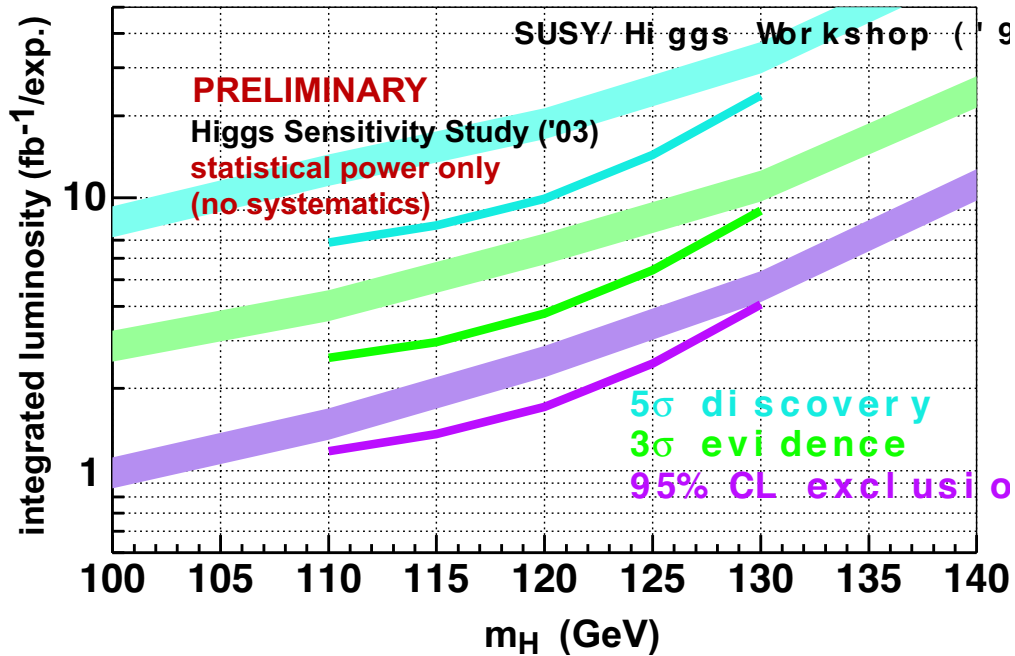
$D\bar{O}$ work with artificial neural networks



and optimization of cuts:



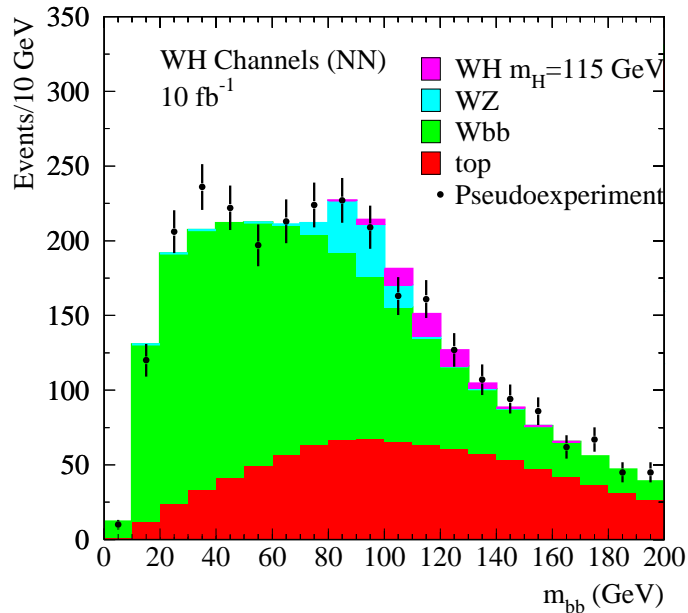
Basic conclusion: the 1998-99 study was not seriously wrong.



- Note that systematics have not been taken into account.
- It appears that with $\mathcal{L} \sim 4 - 5 \text{ fb}^{-1}$, CDF+DØ would exclude SM Higgs if not there up to $m_h \sim 130 \text{ GeV}$ – the range dictated by the MSSM.
- For $\mathcal{L} \sim 8 - 10 \text{ fb}^{-1}$, might find 3σ evidence.
- *This is not final – joint report coming very soon.*

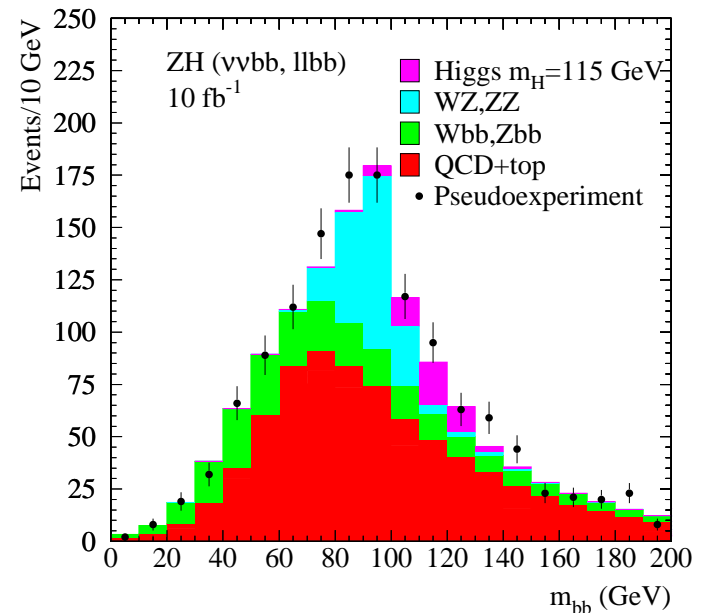
The signals, however, will not be dramatic:

$p\bar{p} \rightarrow W h$ with $W \rightarrow \ell\nu$



This is a statistically 'unlucky' case...

$p\bar{p} \rightarrow Z h$ with $Z \rightarrow \ell^+\ell^-, \nu\bar{\nu}$



This is a statistically 'typical' case...

(but sometimes they aren't so visual – as we will see...)

Luminosity Expectations for the TEVATRON

Currently,

- We have $\sim 190 \text{ pb}^{-1}$ on tape –
- this is $>80\%$ of the data delivered.
- Physics running started in February, 2002

projections for fiscal year 2009:

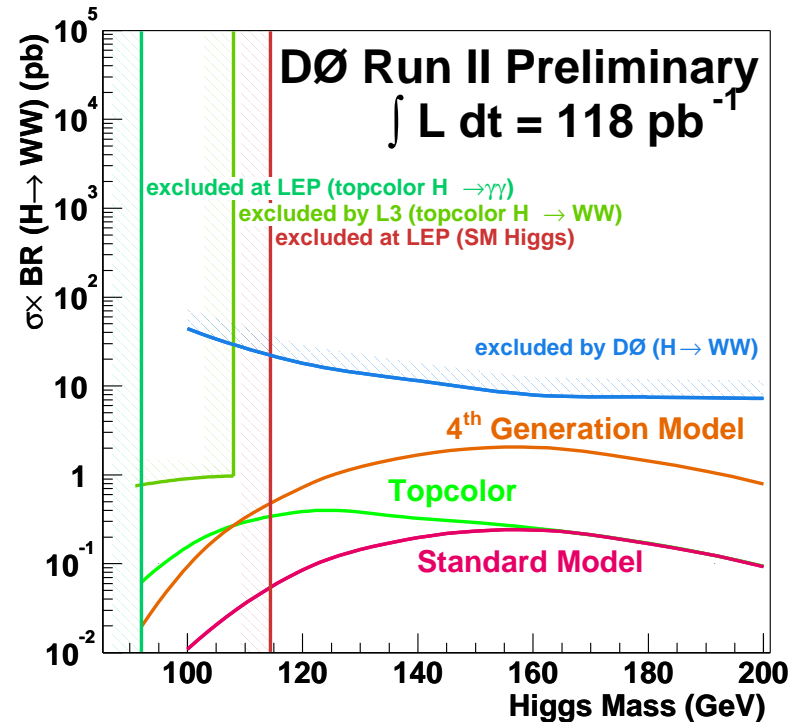
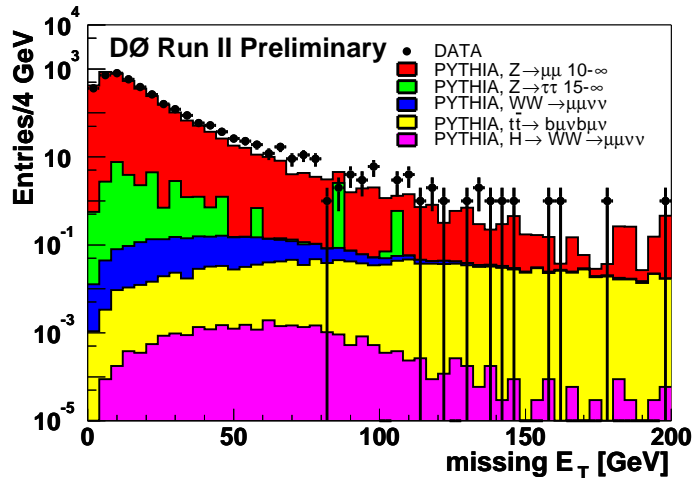
$$\begin{aligned} \text{'base'} \quad \mathcal{L} &\sim 4.4 \text{ fb}^{-1} \\ \text{'design'} \quad \mathcal{L} &\sim 8.6 \text{ fb}^{-1} \end{aligned}$$

→ anticipate achieving $\mathcal{L} \sim 1 \text{ fb}^{-1}$ in 2005.

New Higgs Results from the TEVATRON

From $D\bar{O}$: Search for $h \rightarrow W^+W^-$ with $W \rightarrow e\nu$ or $\mu\nu$.
 ... important in high mass region $140 < m_h < 190$ GeV.

- two energetic, isolated leptons + large E_T
- large SM rates eliminated by topological cuts
- note similarity with continuum $p\bar{p} \rightarrow W^+W^-$
- limit $\sigma \times Br < 8$ pb about $100 \times \sigma(h)$



From CDF: $A \rightarrow \tau^+\tau^-$ in RUN I.

The MSSM provides an opportunity at low m_A and high $\tan\beta$ –
 $\sigma \times Br$ in the hundreds of pb!

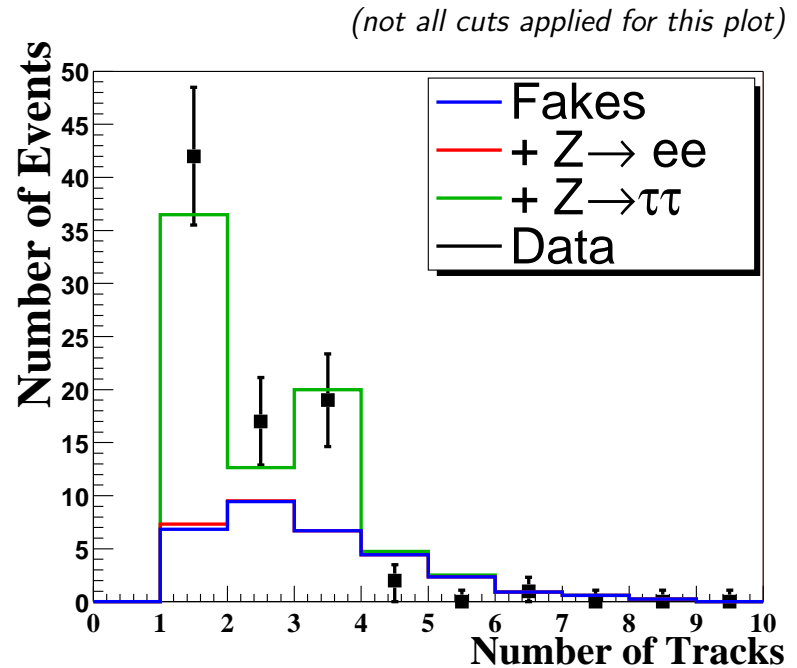
Experimentally, this is a very challenging analysis.

CDF extracted a clear sample of hadronic τ 's.

Expect 53 ± 7 (half QCD & half $Z \rightarrow \tau^+\tau^-$)
 Observe 47.

Unfortunately, sensitivity is far from the
 $m_A \rightarrow \tau^+\tau^-$ signal, even for $\tan\beta = 50$.

Will be much better in RUN II thanks to
 dedicated triggers.



(more on taus later)

DØ is making the first steps toward a Higgs limit in $h \rightarrow Wb\bar{b}$

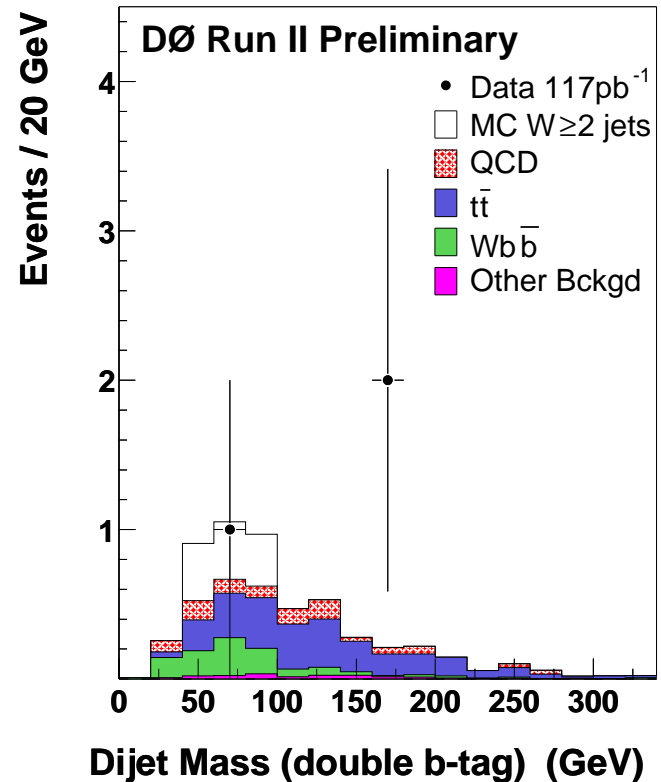
Higgs is on the other side of Top.

Select events with a high- p_T lepton
and two b-tagged jets.

expect 5.5 ± 1.6 events,
including ~ 1 event from $Wb\bar{b}$
observe 3 events

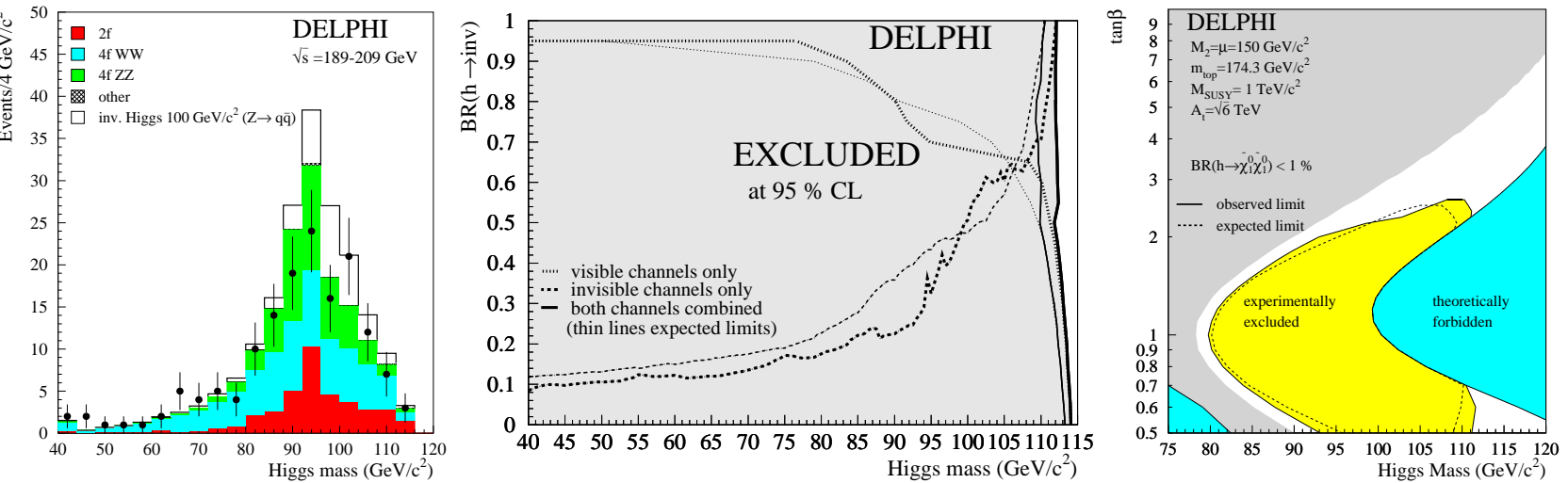
upper limit of 33.4 pb at 95% C.L.

(SM Higgs cross section < 1 pb.)



New Higgs Results from LEP

While the TEVATRON experiments focus on the ‘standard’ Higgs signatures and channels, the efforts at LEP have been concentrated on stranger scenarios. . .



$h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$ can dominate for some choices of MSSM parameters.

DELPHI searched for *invisible* Higgs. Analysis relates to $e^+e^- \rightarrow Zh$ with $Z \rightarrow \nu\bar{\nu}$.
The DELPHI limit is nearly as stringent as SM Higgs!

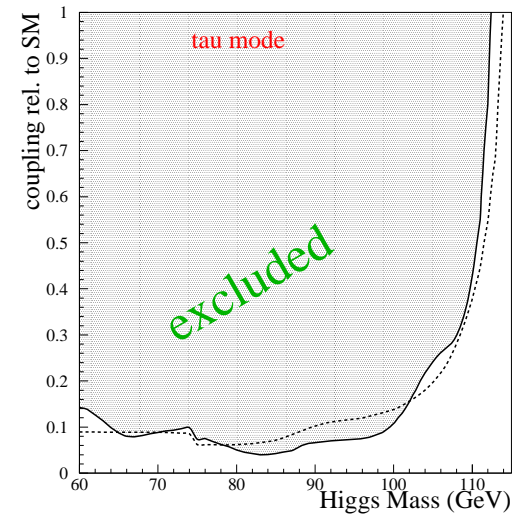
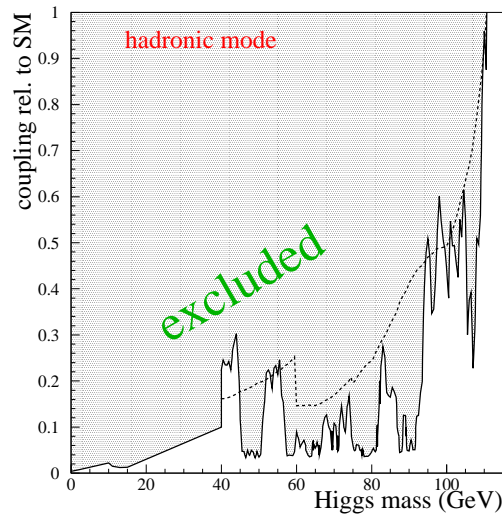
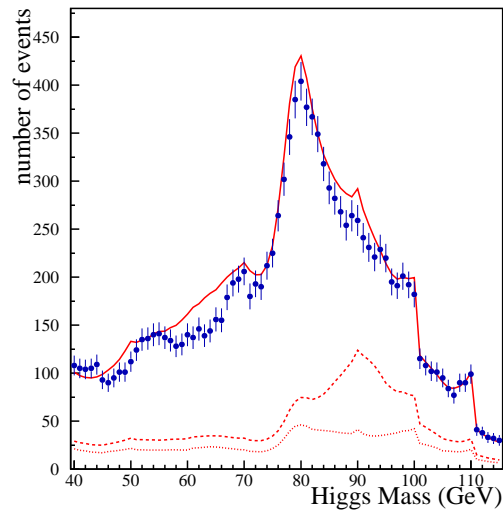
Flavor-Independent Higgs Searches

A Higgs with $m_h < 140$ GeV decays mainly to $b\bar{b}$ at tree-level.

However, radiative corrections can change this dramatically.

→ perform a flavor-independent search: abandon b-tagging and rely on kinematics.

example: ALEPH $l^+l^-q\bar{q} + \tau^+\tau^-q\bar{q} + 4\text{-jet}$ channels



lower limit on m_h is 110 – 112 GeV

(See also: DELPHI and OPAL contributions to this conference.)

Searches for Bosophilic Higgses

In a similar vein, consider Higgs which decay primarily to boson pairs $h \rightarrow VV$.

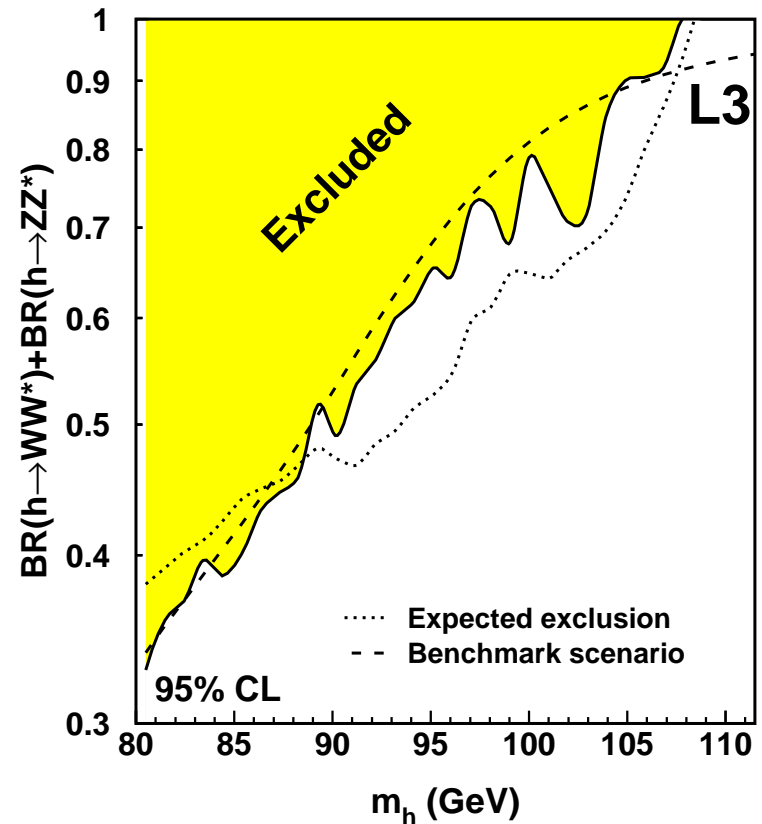
example: L3

benchmark scenario: assume σ_{SM} ,
'turn off' all decays to fermions

$h \rightarrow \gamma\gamma$ dominates for $m_h < 40$ GeV.

combine many channels depending on
decays of Z and of V 's.

$m_h > 108$ GeV
for $\text{Br}(h \rightarrow WW + ZZ) = 1$.



CP-Violation in Higgs Decays

CP violation may be induced through radiative corrections (esp. \tilde{t}_i)

This may help explain the baryon asymmetry of the universe. (Pilaftsis & Wagner, 1999) (Carena *et al.* 2000)

In general, three mass eigenstates $\{H_1, H_2, H_3\}$ are mixtures of the CP eigenstates $\{h, H, A\}$.

Couplings to gauge bosons can vary widely, and the lightest one H_1 might not be produced at LEP at all!

New OPAL analysis of ‘Higgsstrahlung,’ ‘Associated Production,’ and ‘Yukawa Production’ → CP-conserving scenarios already well known:

$$m_h, m_A > 84 \text{ GeV and } \tan \beta \sim \mathcal{O}(2) \text{ is excluded}$$

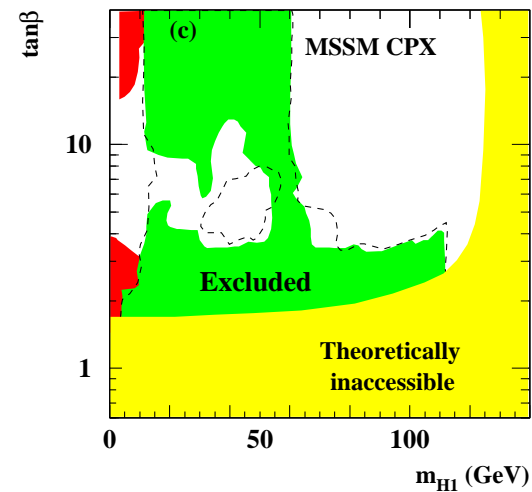
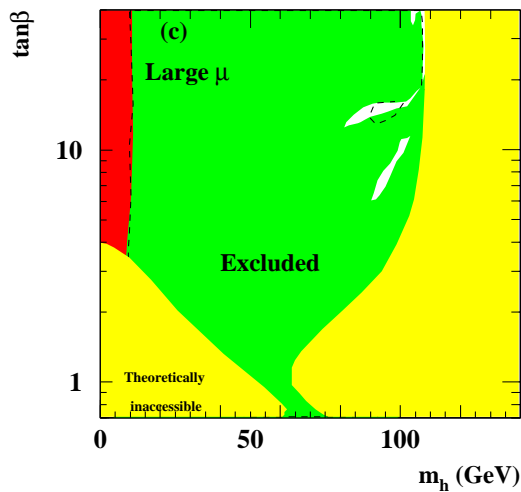
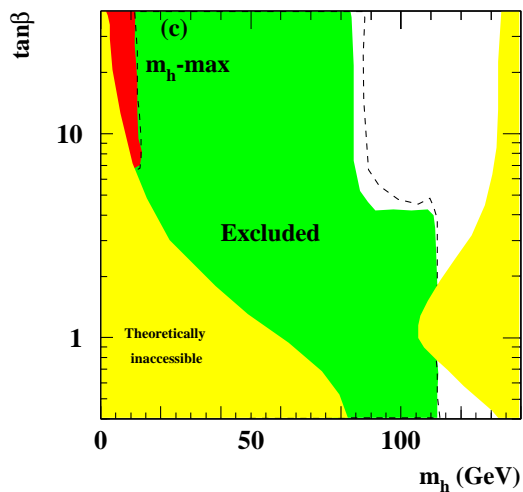
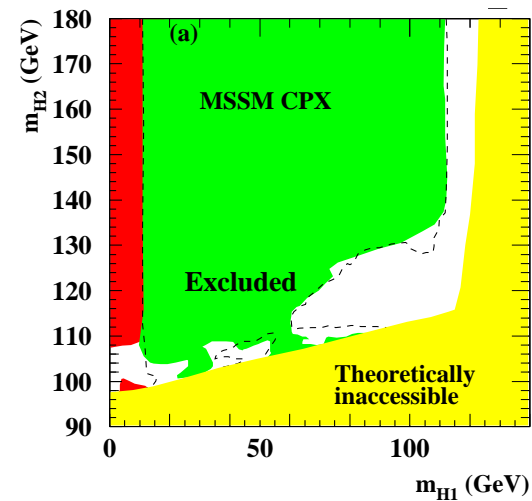
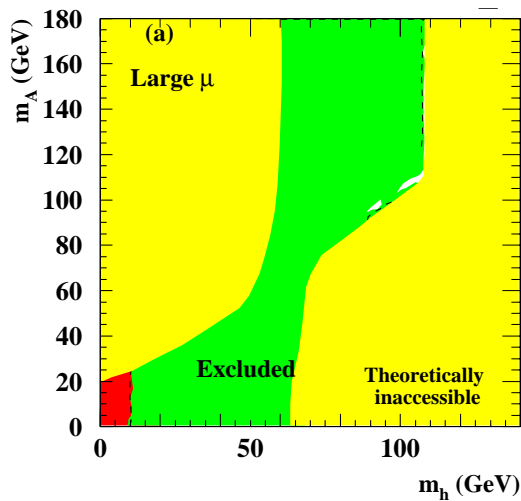
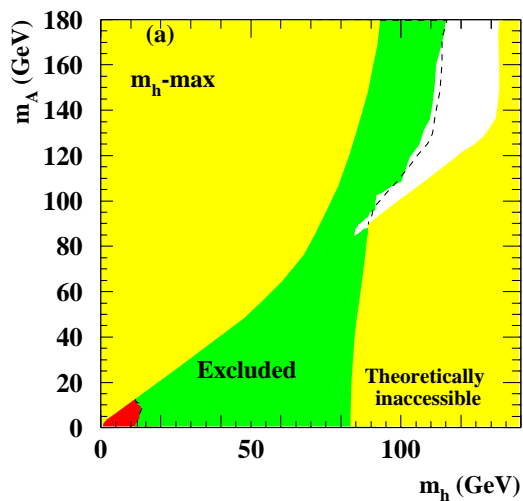
But there are some interesting special cases:

- “large μ ” – suppressed decays to $b\bar{b}$ due to large negative corrections from SUSY loops
flavor-independent searches are important here.
- “gluophobic” – stops and tops cancel in $g - g - h$ loops (a big problem for LHC).
- “small α_{eff} ” – suppression of decays to $b\bar{b}$ and $\tau^+\tau^-$ due to additional mixing in Higgs sector

CP-violating scenario:

- mixing effects in Higgs sector are large when $\text{Im}(\mu A_t)$ is large and/or m_S is small.
- dramatically different phenomenology when $\arg(A_t) \sim 90^\circ$

(Benchmarks suggested in Carena, Ellis, Pilaftsis & Wagner, 2000)



maximum m_h scenario

large μ scenario

a tough CP-violating case

Super★Symmetry★Searches

We have many many scenarios to consider.

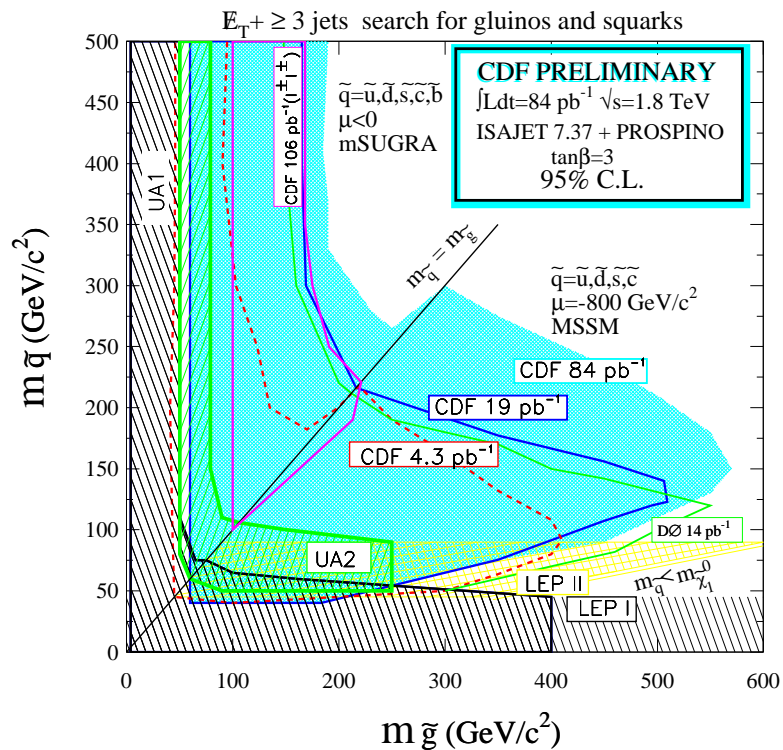
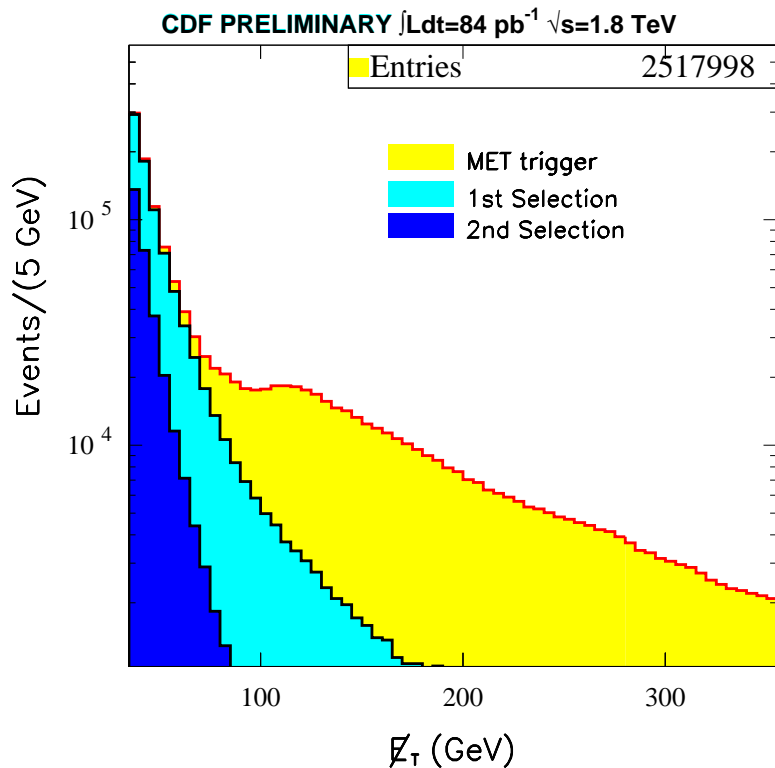
In different cases, the experimental signatures are similar.

So, we will organize the discussion around the elements of the searches, namely

*jets, missing energy, leptons, taus, photons,
and strange tracks!*

Jets (+ Missing Energy) (+ Leptons)

From RUN I, the lessons on reducing a huge MET sample to a few, constraining events:



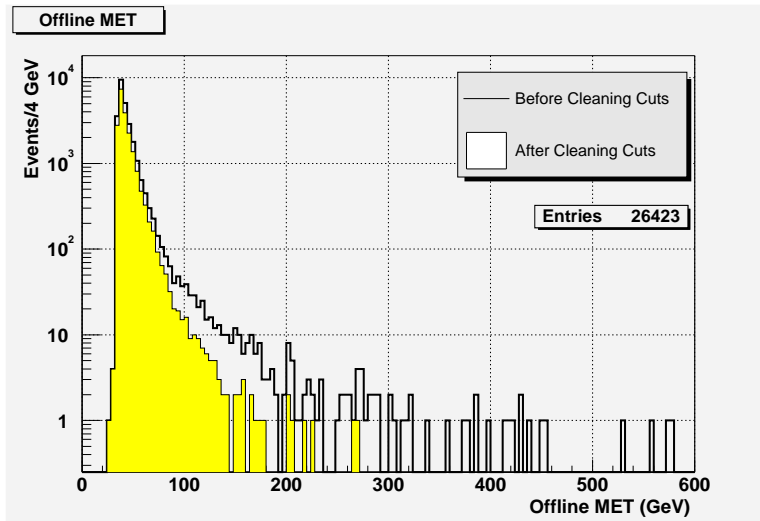
Most stringent bounds in mSUGRA $\longrightarrow m_{\tilde{g}} > 195 \text{ GeV}$, and $> 300 \text{ GeV}$ when $m_{\tilde{q}} \approx m_{\tilde{g}}$.

NB: much better than expected a priori...

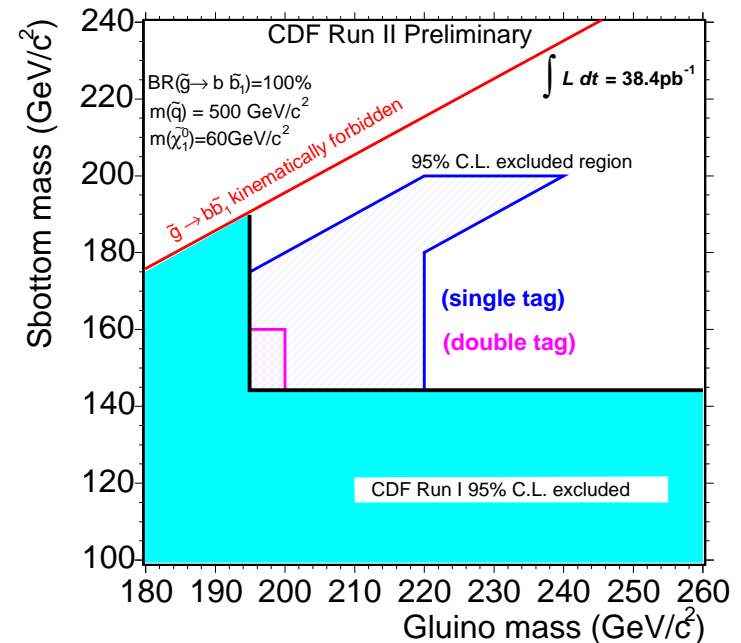
From RUN II, a new analysis looking for $\tilde{g} \rightarrow b\tilde{b}_1$ (CDF)

Take advantage of the large cross sections for the production of gluinos at a hadron machine.

- much better b-jet trigger, greatly improved acceptance
- b -tagging (SVX algorithm)
- currently using only a fraction of available data



Note how much cleaner than in RUN I.



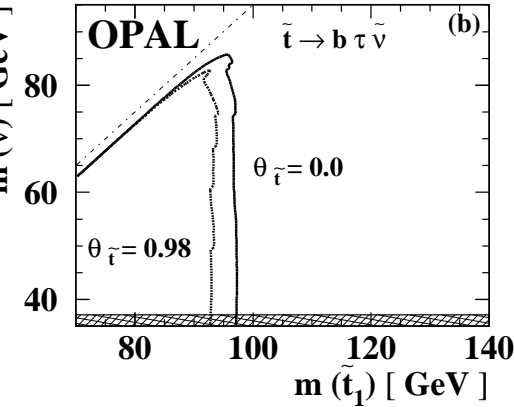
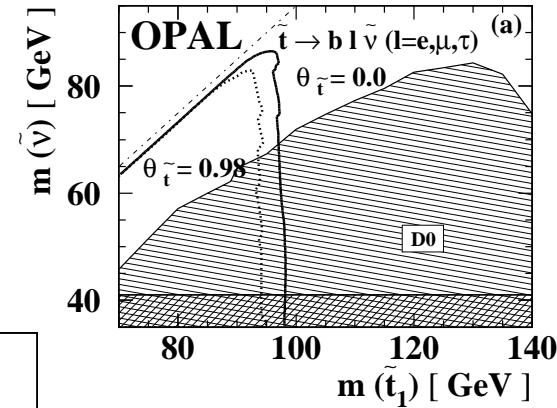
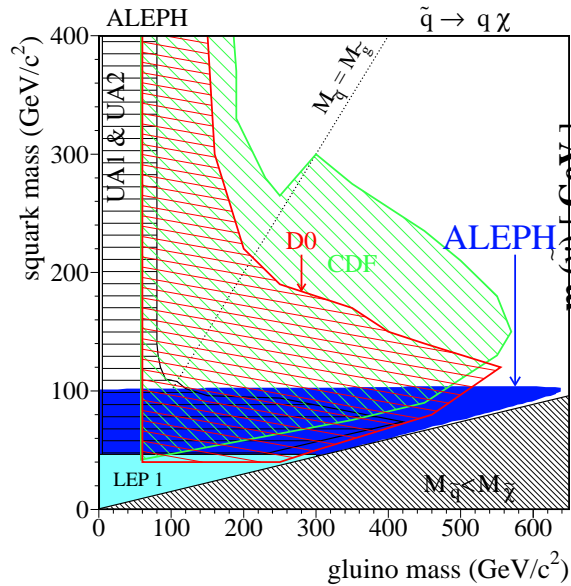
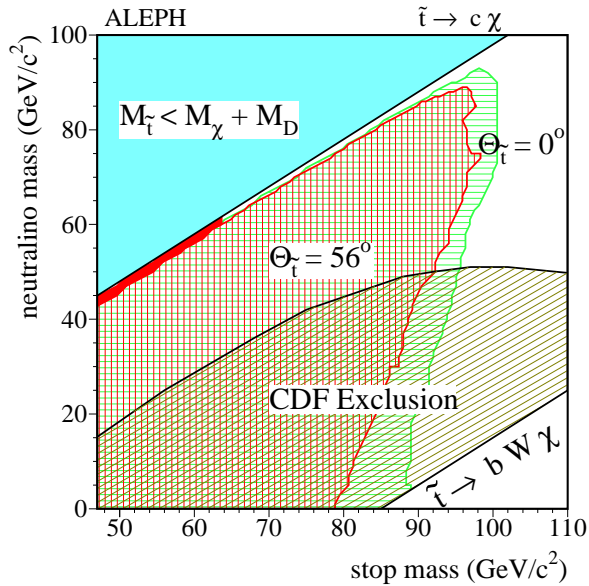
Stop & Sbottom searches at LEP – many varieties. . .

several \tilde{t}_1 searches from ALEPH:

- $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$ (and $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$)
- $\tilde{t}_1 \rightarrow b\tilde{l}\tilde{\nu}$
- $\tilde{t}_1 \rightarrow bff\tilde{\chi}$

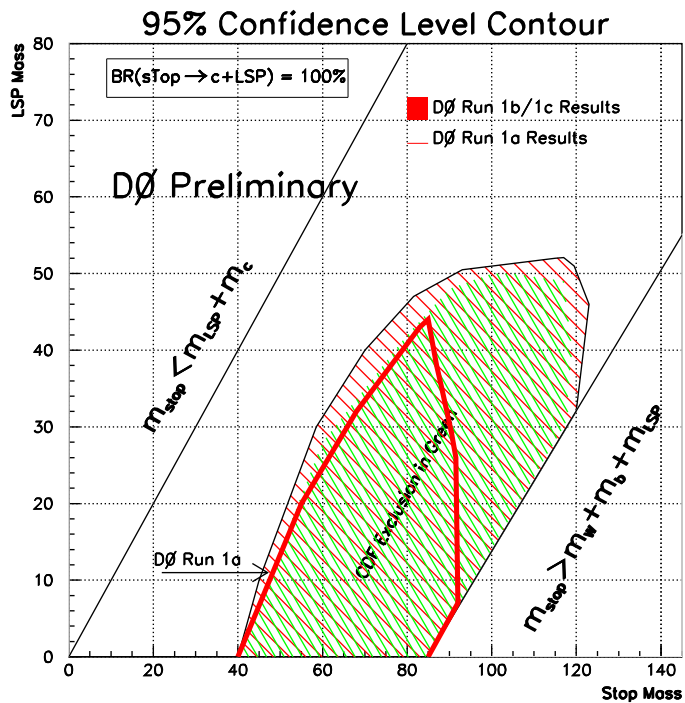
special effort from OPAL on τ channel $\tilde{t}_1 \rightarrow b\tau\tilde{\nu}_\tau$.

ALEPH result reinterpreted for generic \tilde{q} :

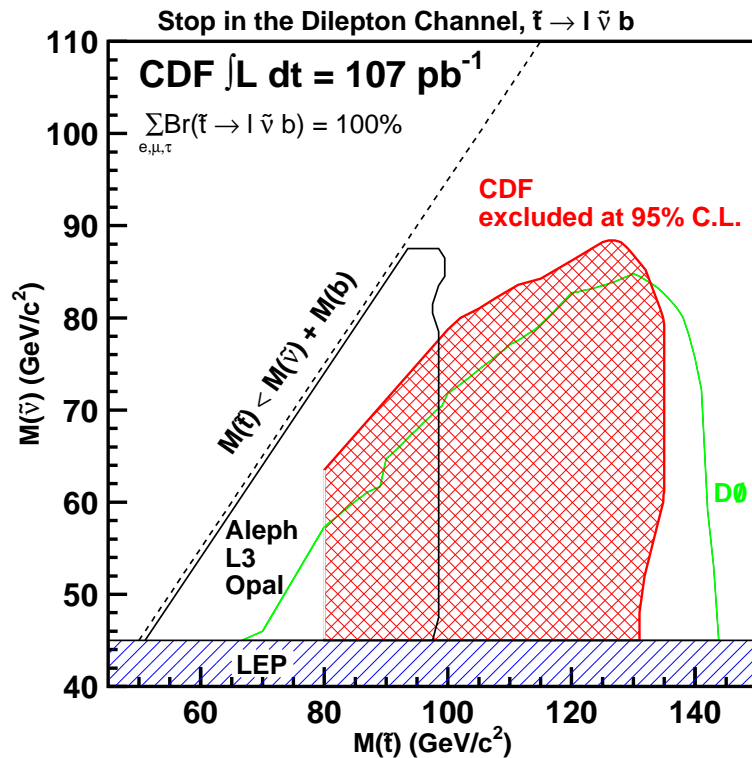


(... finishing-up stop searches from Run I ...)

New DØ analysis of $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$



New CDF analysis of $\tilde{t}_1 \rightarrow b\tilde{l}\tilde{\nu}$



Stay tuned for updates from the Run II data...

More about Leptons

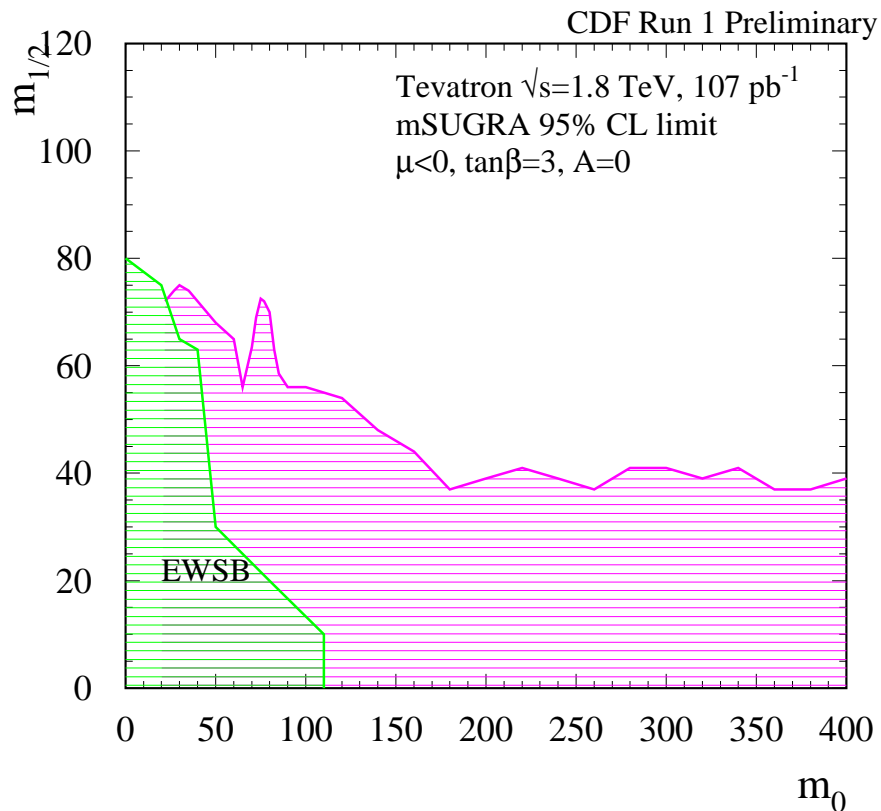
Lepton-based signatures are useful for finding $p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ (e.g. 'tri-lepton' analysis)

CDF is completing an extension of the search for gauginos in the "like-sign di-lepton" channel

$$p\bar{p} \rightarrow \ell^\pm \ell^\pm + X$$

from Run I.

After a careful removal of non-isolated leptons and a study of fakes, zero events were observed where ~ 0.6 were expected.



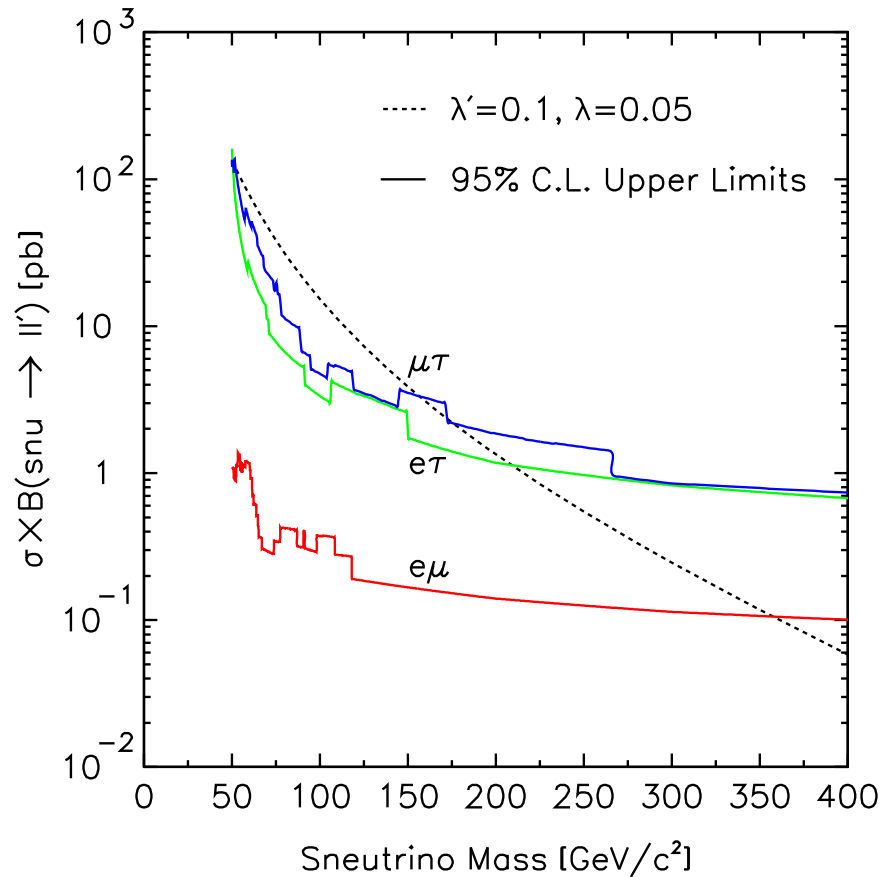
Derive limits in the mSUGRA model, accept small contributions from other processes. Not as constraining as Jets+ E_T . Look forward to Run II, combined with tri-leptons.

A related sample is the
“opposite-sign, different-flavor”
channel which has been used to con-
strain R -parity violating $\tilde{\nu}$ production.

$$d\bar{d} \rightarrow \tilde{\nu} \rightarrow \ell^+ \ell'^{-}$$

The actual limits depend on the as-
sumed values of the R -parity violating
couplings, λ and λ' .

CDF Run I

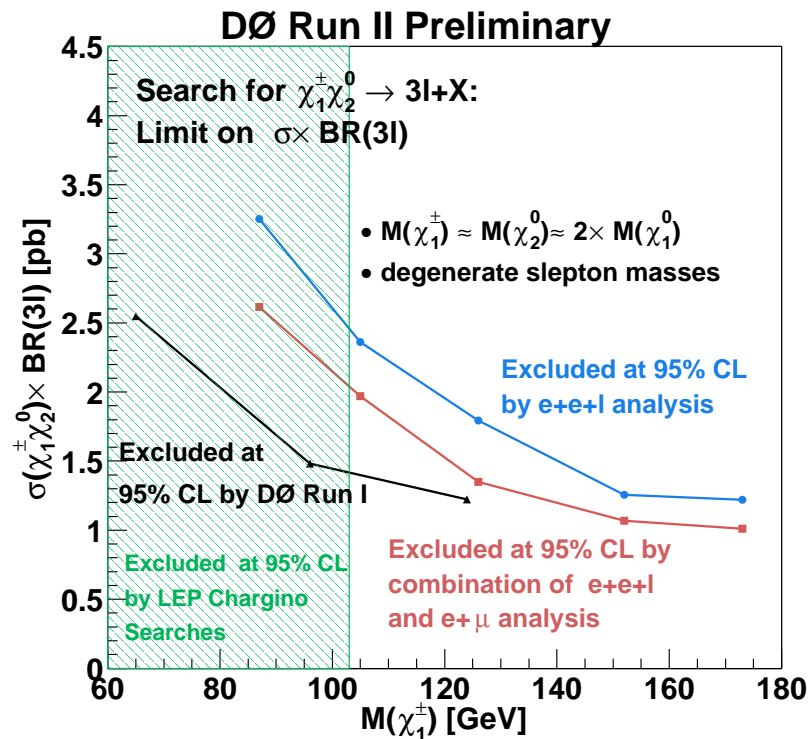


Lepton-based Searches in Run II

$D\emptyset$ has the first Run II result in the *tri-lepton* search!

- dedicated search in ee +track sample
- reinterpret model-indep. $e\mu$ +track search
- both require high- p_T , well identified & isolated leptons, large missing energy, and a single isolated track
- SM backgrounds are low, dominated by W +jets & W^+W^-
- combine results to constrain

$$\begin{aligned}
 p\bar{p} &\rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow lee\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0 \\
 &\rightarrow le\mu\nu \tilde{\chi}_1^0 \tilde{\chi}_1^0
 \end{aligned}$$

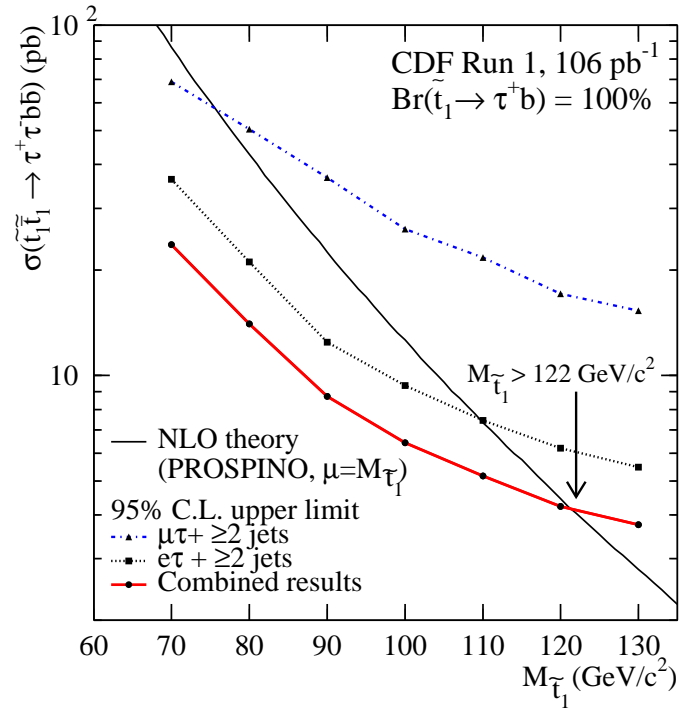
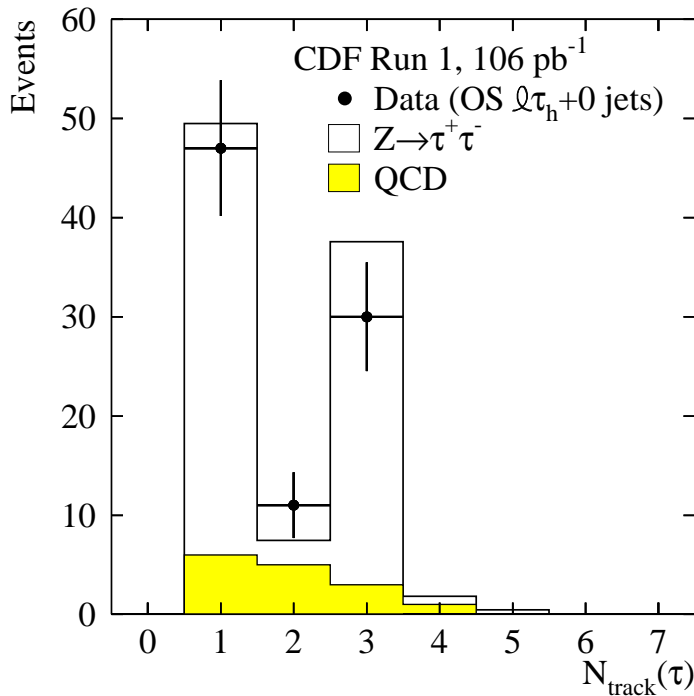


limits compare well to Run I, but are a factor 10 above mSUGRA predictions

Taus, Taus, Now Everyone has Taus

One of the more difficult challenges in Run I was to search for new particles based on τ -signatures. It was pointed out that these signatures might be crucial.

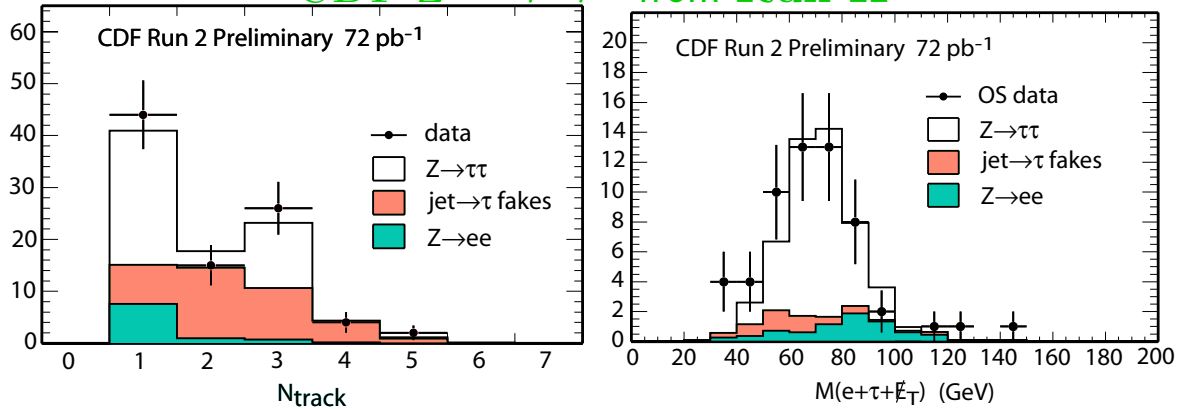
τ -based searches did eventually succeed – here is a good example from Run I:
R-parity violating $\tilde{t}_1 \rightarrow b\tau$ decays (CDF).



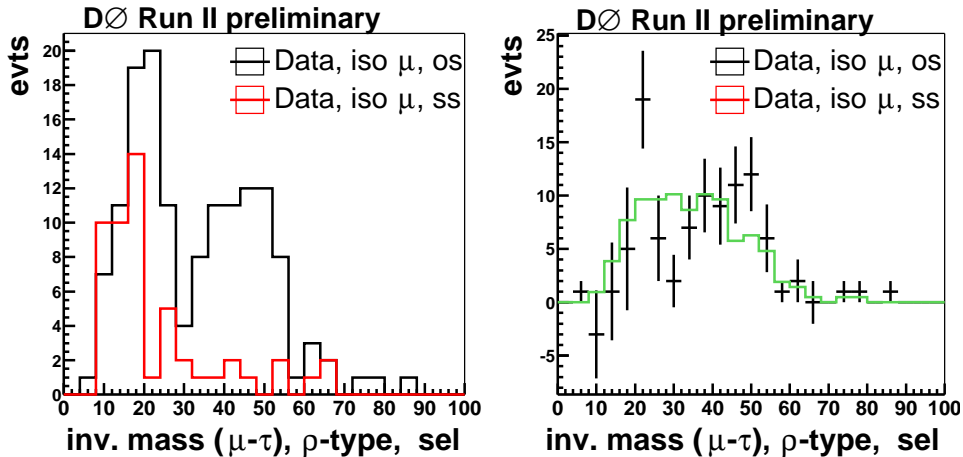
(Recall also the $A \rightarrow \tau^+\tau^-$ result quoted earlier.)

For Run II, the TEVATRON collaborations put special emphasis on better triggers for τ signals. Much has already been achieved in establishing good τ signals (from SM processes).

CDF $Z \rightarrow \tau^+ \tau^-$ from Run II



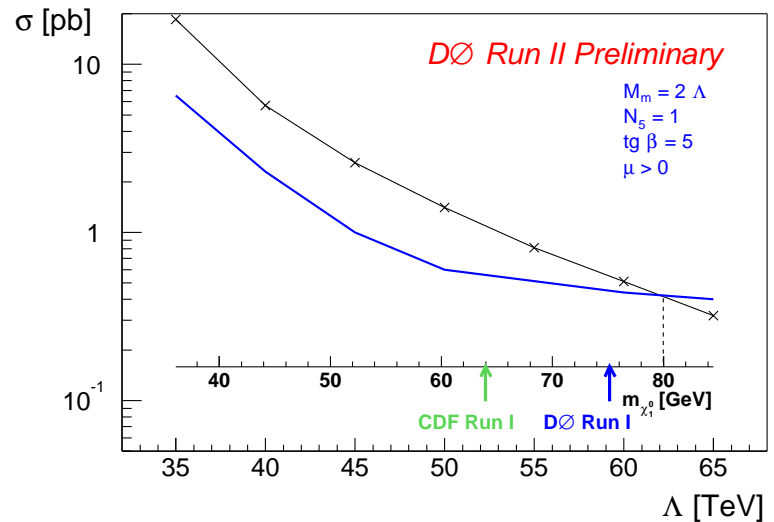
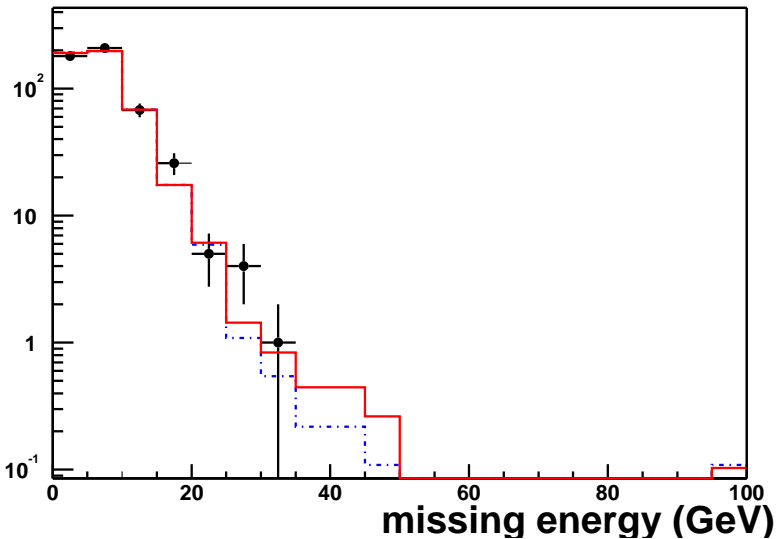
DØ $Z \rightarrow \tau^+ \tau^-$ from Run II



This case is motivated mainly by the gauge-mediated scenario, which has many theoretical virtues. In truth, it received a lot of attention some years ago when a single spectacular event was publicized by the CDF Collaboration.

Naturally there has been lots of attention to photon-based searches in Run II.

$D\bar{O}$ is ready with $\gamma\gamma + \cancel{E}_T$:

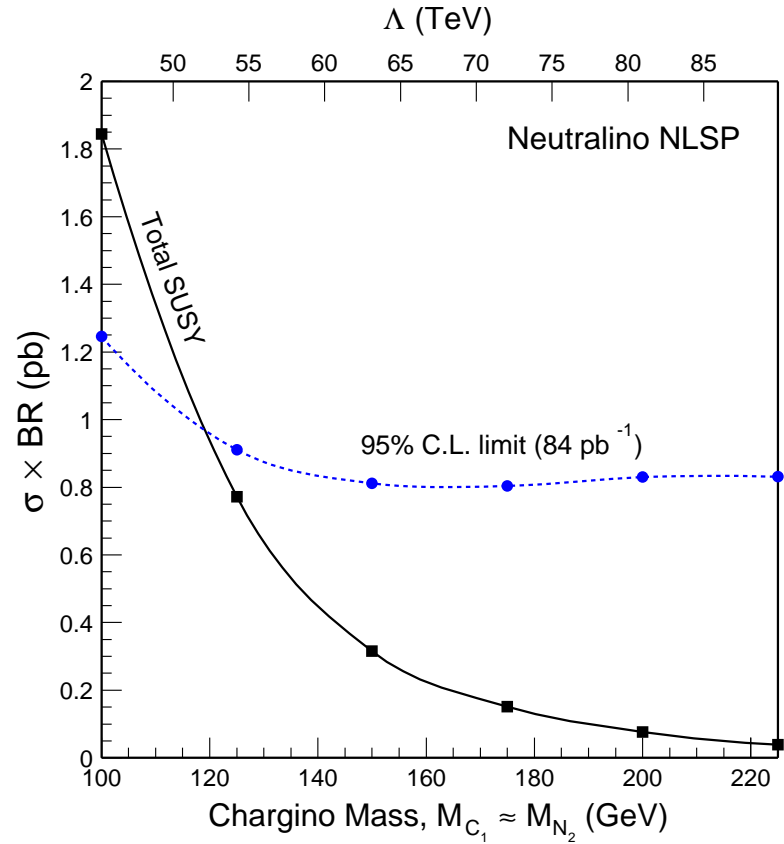
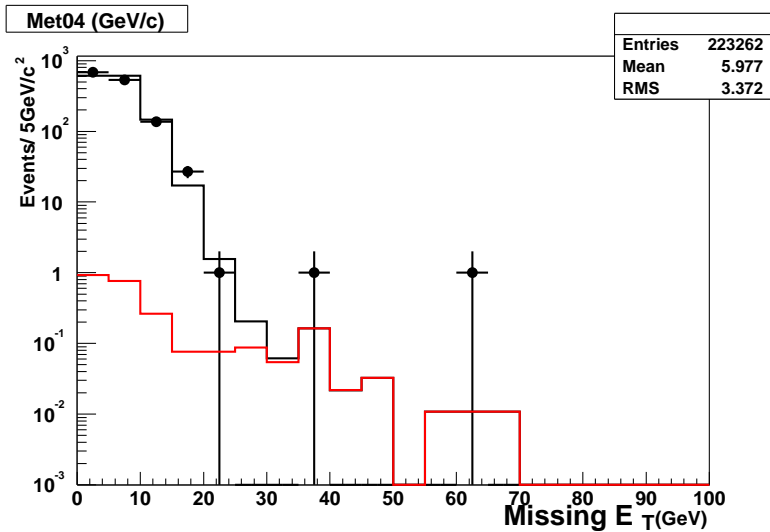


Select two central EM clusters, $E_T > 20$ GeV, & \cancel{E}_T should not point along photon (or jet) directions. Normalize QCD background in $\cancel{E}_T < 15$ GeV region. Optimal cut is $\cancel{E}_T > 35$ GeV.

Expect 1.4 ± 0.3 , observe zero.

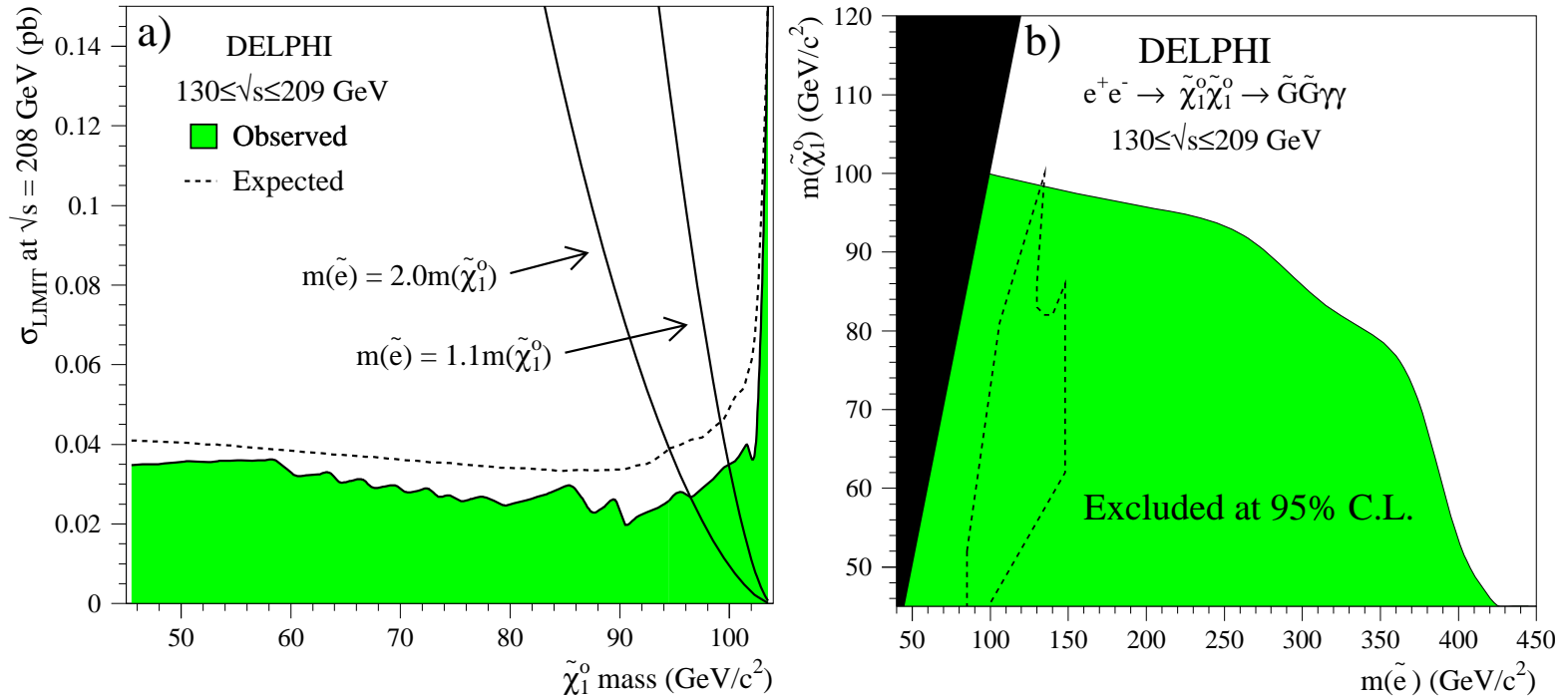
CDF has obtained very similar results:

- 2 isolated photons, $E_T > 13$ GeV
- \cancel{E}_T separated from photons & jets
- require $\cancel{E}_T > 25$ GeV
- expect 0.6 events, observe 2 (84 pb^{-1})
- highest \cancel{E}_T is 64.6 GeV



The LEP collaborations continue to investigate these channels, too.

The final state is $2\gamma + E_{\cancel{T}}$.

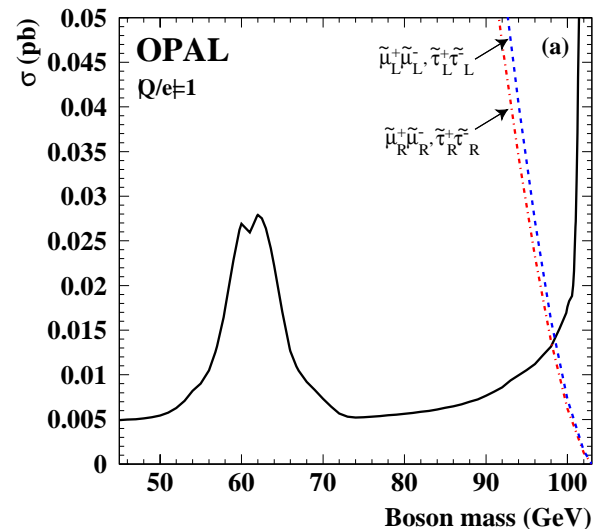
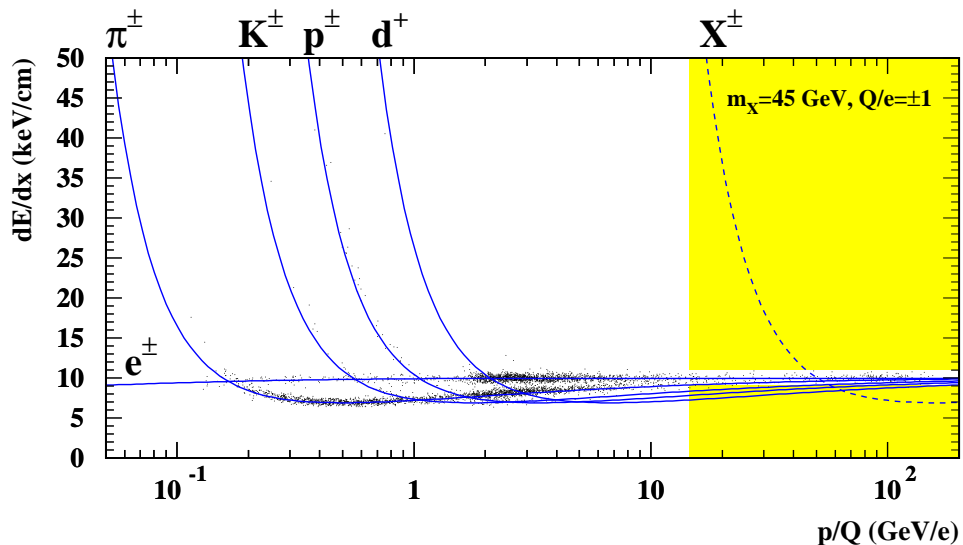


Enough data have been collected that the entire parameter region favored by the one famous CDF event ($ee\gamma\gamma E_{\cancel{T}}$) is excluded. Here is the result from DELPHI data.

Strange Tracks, etc.

If a new particle (e.g., $\tilde{\mu}$, $\tilde{\tau}$ or \tilde{t}_1) is stable and heavy, it will ionize the gas in the tracking chambers anomalously. Here are the latest bounds from OPAL:

OPAL

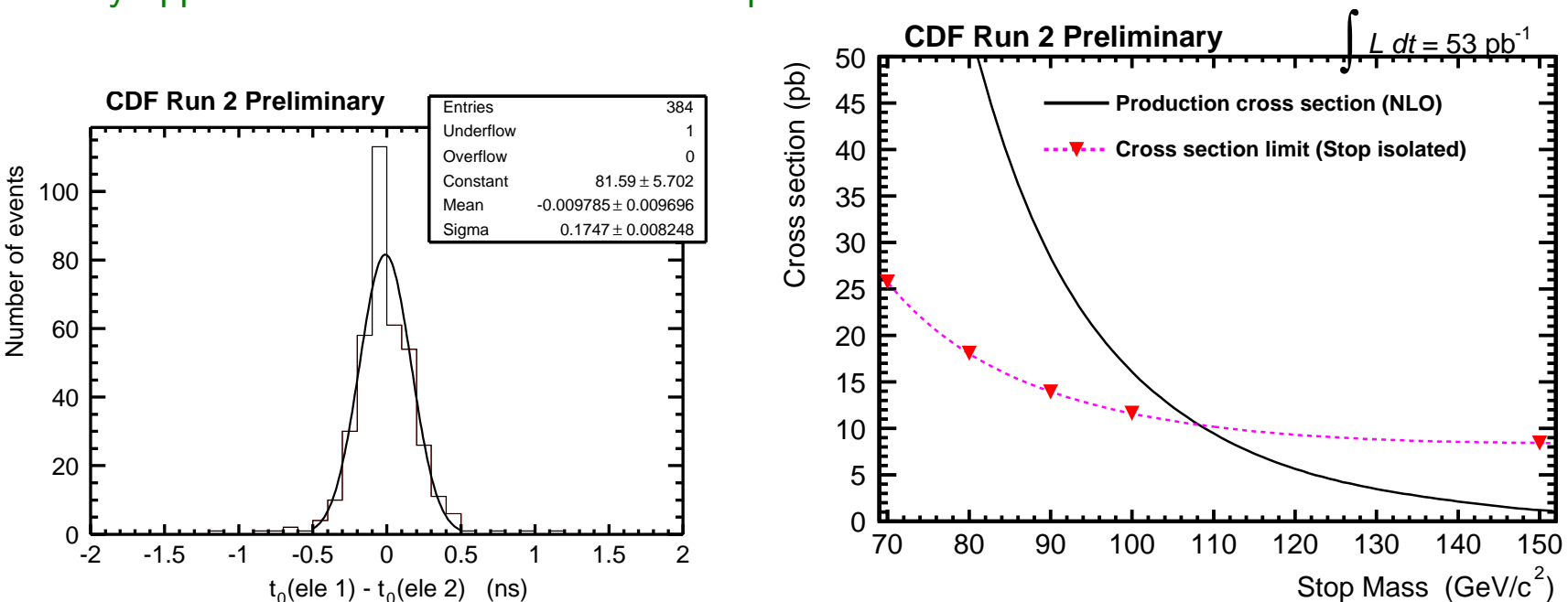


Also from LEP, and along these lines, are

- OPAL search for particles decaying at large distances from the IP
- ALEPH search for stable squarks and gluinos

CDF have also pursued this kind of search using ionization measurements in their upgraded & improved central outer tracker, and the new time-of-flight system –

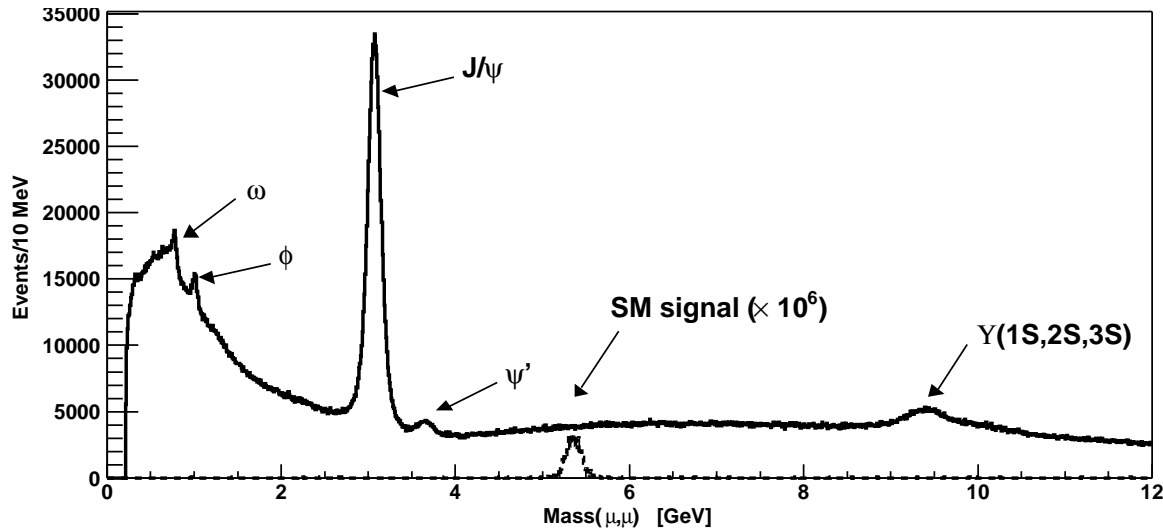
They applied their results to the stable-stop case.



- ToF system gives resolution of ~ 125 ps
- analysis with 53 pb^{-1} is sensitive to $M_{\tilde{t}_1} \approx 110 \text{ GeV}$

Finally, there are excellent new **TEVATRON** results on the decay $B_s \rightarrow \mu^+ \mu^-$:
 (The old CDF result from Run I is $\text{Br}(B_s \rightarrow \mu^+ \mu^-) < 2.0 \times 10^{-6}$ at 90% C.L.)

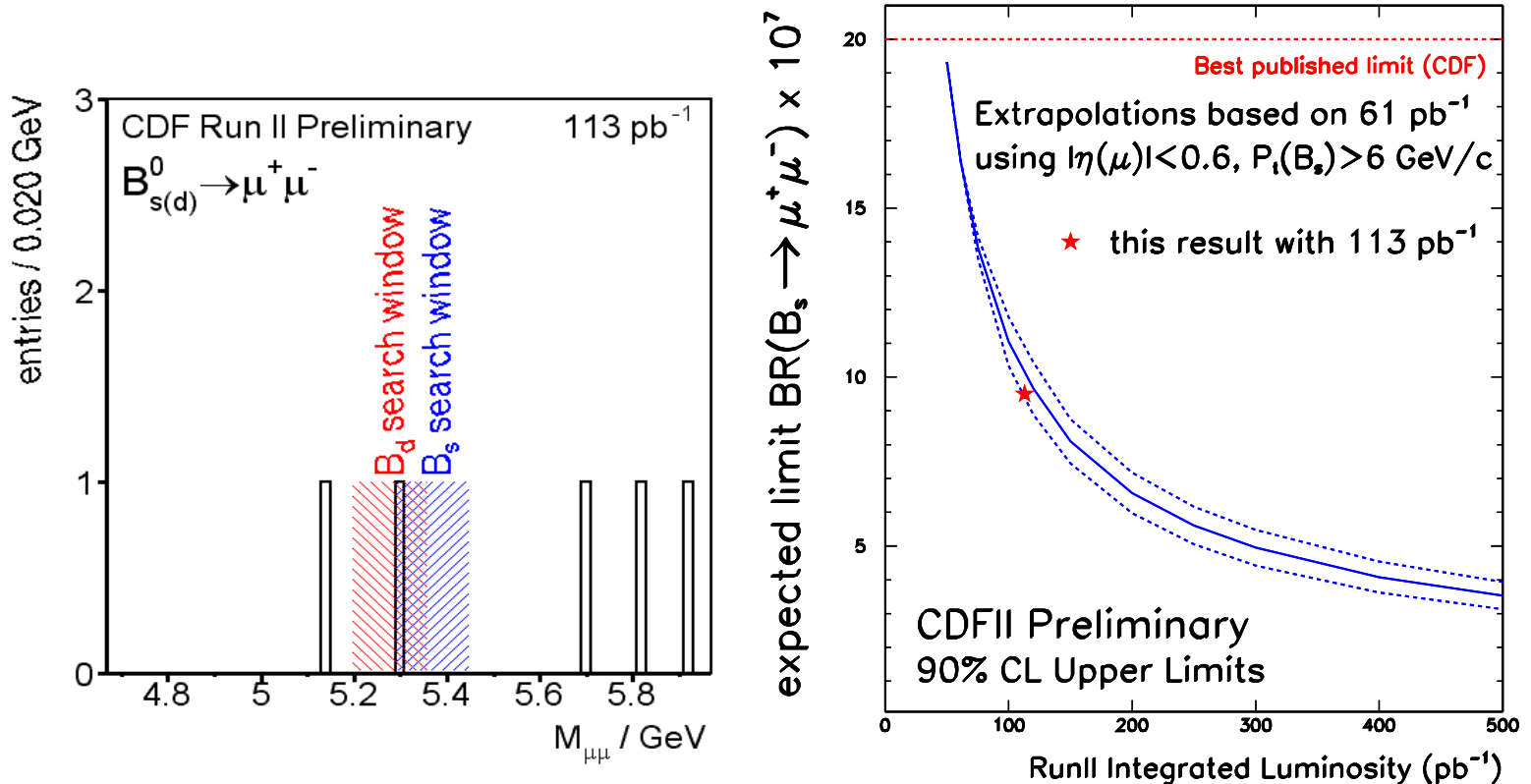
The challenge is formidable (see plot from DØ):



To tackle this, require:

- a good, displaced vertex pointing back to the IP
 - relatively high p_T for the muon pair
 - good muon isolation
- find 3 events in window, expect ~ 3.4
 $\implies \text{Br}(B_s \rightarrow \mu^+ \mu^-) < 1.6 \times 10^{-6}$ at 90% C.L.

In the CDF analysis, find one event, expect $\sim 1/2$



CDF bound: $\text{Br}(B_s \rightarrow \mu^+ \mu^-) < 0.95 \times 10^{-6}$ at 90% C.L. (1.2×10^{-6} at 95% C.L.)

– more than a factor two lower than Run II!

Light A^0 could lead to $\text{Br}(B_s \rightarrow \mu^+ \mu^-) \sim 10^{-7}$...

Conclusions

- The field of Higgs and SUSY Searches is super-active!
- Higgs and SUSY searches at LEP are filling in holes (and sometimes uncovering them, too).
- The TEVATRON collaborations are cautiously positive about the Higgs search. – there can still be a real impact for SM-like Higgses.
- SUSY searches at the TEVATRON are getting over the bar – some first real results are now available with many others soon to appear. The TEVATRON collaborations are looking forward to a wide variety of new particle and new phenomena searches. (See talk by E.Perez for many other interesting results.)
- What we need now is more data!

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